Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Regional and Local Geothermal Potential Evaluation: Examples from the Great Basin, USA, Iceland and East Africa

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Keywords: Structure, permeability, Iceland, Basin and Range, Great Basin, East Africa Rift, Kenya, fault, geothermal fairway

ABSTRACT

In both tectonically and magmatically mediated geothermal systems, geologic structures play a crucial role in focusing geothermal fluid circulation in the upper crust. In a variety of geothermal provinces worldwide, normal and strike-slip faults, caldera related faults, as well as fractures and fissures related to dikes and other magmatic intrusions generate the fracture permeability utilized for geothermal circulation. Localities where the above structures intersect and interact are characterized by the most robust generation and maintenance of fracture permeability, and therefore are the most favorable conduits for geothermal circulation. We present an evaluation of the structural geometries that tend to generate high density faulting and fracturing and an evaluation of the orientations of those structures with respect to the ambient stress conditions in three regions of high geothermal potential; The Great Basin, USA, Iceland, and east Africa. These analyses provide first-order constraints on areas that have favorable conditions for permeability and where future exploration for geothermal resources could be focused. In the Great Basin, USA, fault step-overs, fault terminations and accommodation zones are among the most common structural settings of known geothermal activity. Analysis of the geometry of these structures with respect to the ambient stress conditions reveals locations where faults associated with these structures are favorably oriented for enhanced fracture permeability. In magmatically active extensional provinces, like Iceland and east Africa, heat associated with shallow magmatic intrusions beneath volcanic centers drives geothermal circulation in near-surface fracture permeability conduits. Accentuated fault and fracture density and fracture permeability is generated by both axially oriented faults and fractures associated with axial rift zones and radially oriented structures near volcanic centers. Although heat from magmatic intrusion is most robust at volcanic centers, a high density of young intrusions may actually result in decreased permeability through closing of fracture networks. The locations of these three types of features; axial faults and fractures, radial structures, and young magmatic intrusions, all play a critical role in determining the most favorable locations for fracture permeability and fluid flow in magmatic geothermal systems. Within and around the margins of volcanic centers, where radial structures associated with volcanic centers interact and intersect with axially oriented structures associated with axial extension are the most favorable locations for fracture permeability and geothermal fluid circulation in magmatic extensional geothermal systems.

1. INTRODUCTION

Economically viable geothermal circulation requires adequate permeability in the near-surface. As geothermal development transitions to focus on blind and unconventional resources, assessing, characterizing, and locating permeability pathways in such systems, prior to expensive drilling investment, will become increasingly important. Assessments of geothermal systems worldwide have indicated that near surface permeability is controlled by fault and fracture systems with a variety of structural geometries (e.g. Flóvenz and Sæmundsson, 1993; Bibby et al., 1995; Curewitz and Karson, 1997, 1998; Gudmundsson, 2000a; Rowland and Sibson, 2004; Faulds et al., 2006, 2011, 2013; Wallis et al., 2012). The spatial arrangement of these structures relative to one another, the density of secondary faults and fractures associated with these structures, and the orientations of faults and fractures relative to prevailing stress conditions all effect their potential for permeability and therefore their potential to act as conduits for geothermal fluids. We examine four sets of structures known to generate fracture permeability and host geothermal systems in magmatic and amagmatic geothermal systems; fault terminations, fault step-overs, accommodation zones, and magmatic rift segments. We examine the locations of highest fracture permeability potential within each. The resultant conceptual models provide indications of the most favorable locations for fracture permeability and can be used to guide exploration activities in analogous geothermal prospects worldwide.

2. BACKGROUND

In both tectonically and magmatically mediated geothermal areas, permeability is highly variable spatially, temporally, and in magnitude. A relatively narrow range of permeability is optimal for economic-scale circulation (Wisian and Blackwell, 2004). Permeability can vary well beyond this range, from sufficiently able to conduct geothermal fluid flow to effectively impermeable, and this variation can occur on the scale of 10s to 100s of meters (Fairley et al., 2003; Fairley and Hinds, 2004). This fine-scale variation underlines the need for regionally and locally applicable conceptual models that help define favorable geothermal prospects and especially the most favorable permeability domains (i.e. exploration targets) within those prospects.

In the Great Basin, USA, anomalously high heat flow, associated with Cenozoic extension along with locally elevated permeability associated with abundant Tertiary faulting, provide the requisite heat and permeability for geothermal circulation (Lachenbruch and Sass, 1977; Blackwell, 1983; Blackwell et al., 1991; Wisian and Blackwell, 2004; Faulds et al., 2006). Specifically, geothermal systems hosted by horse-tailing fault terminations, step-overs or relay ramps in normal fault systems, and accommodation zones between fault systems with opposing dip account for 62% of the known and production geothermal systems in the Great Basin

(Faulds et al., 2011). These structural settings are favorable for generating and maintaining fracture permeability in the shallow sub-surface.

In magmatic extensional settings like Iceland and east Africa, the requisite heat and permeability are provided by shallow magmatic activity and abundant faulting and fracturing associated with tectonic and magmatic extension. Similar to tectonically mediated geothermal systems, permeability in magmatic geothermal systems is also generated along normal and strike-slip faults, but faults and fractures associated with magmatic intrusions and caldera-related faults have also been shown to control geothermal fluid flow as well (Flóvenz and Sæmundsson, 1993; Bibby et al., 1995; Curewitz and Karson, 1997, 1998; Gudmundsson, 2000a; Rowland and Sibson, 2004; Wallis et al., 2012). The architecture of the crust in these settings, however, is very complex due to relatively frequent magmatic and tectonic activity (e.g. Gudmundsson, 1995; Siler and Karson, 2009, 2012) and this has complicated the development of conceptual models of the specific structures and structural geometries that host fracture permeability in magmatically mediated geothermal systems. Furthermore, geophysical techniques, most notably magnetotellurics, have proven to be highly effective tools for identification of geothermal reservoirs in magmatic geothermal settings (e.g. Uchida and Sasaki, 2006; Spichak and Manzella, 2009). Still, anomaly hunting, geothermal exploration based on locating geophysical anomalies, has pitfalls if not associated with a conceptual model incorporating all available data (Cumming, 2009). The next generation of blind and unconventional geothermal exploration will require understanding and conceptualization of the nature, character and optimal locations of fracture permeability in order to make informed exploration decisions.

3. PERMEABILITY FAVORABILITY: GREAT BASIN

Horse-tailing fault terminations, step-overs in normal fault systems, and accommodation zones between fault systems with opposing dip are predominant structural settings for geothermal systems in the Great Basin (Faulds et al., 2006, 2011, 2013). However, permeability is highly variable within these areas and not all manifestations of these structural geometries host known geothermal systems. An important tool, therefore, for current and future geothermal exploration is the ability to define the most prospective instances of these structural settings, as well as the areas within them that are most favorable for accentuated fracture permeability.

Fracture permeability within fault step-overs, fault terminations, and accommodation zones is primarily a function of high-density faulting and fracturing, which generates sub-vertical permeability conduits and allows geothermal fluids to upflow from depth. Within the above structural settings, faulting and fracturing is most intense at the tips of faults and at fault intersections where stresses are concentrated (Pollard and Aydin, 1988; Scholz et al., 1993; Curewitz and Karson, 1997). Many Great Basin geothermal systems are characterized by more than one of these structural settings, e.g. a fault step-over within an accommodation zone. These hybrid systems are particularly favorable, as increased structural complexity leads to more fault tips and fault intersections and therefore is favorable for accentuated permeability generation (Faulds et al., 2013).

Fault terminations, fault step-overs and accommodation zones are typically characterized by the interaction, intersection or tip-out of one to several primary faults. In the 'breakdown region,' the zone of stress concentration at the tips or intersections of these primary faults, many secondary faults and fractures are generated, and therefore many secondary breakdown regions are generated as well (Figure 1). The radius of the breakdown region at a fault tip or fault intersection scales as 1% to 10% the length of the fault (Pollard and Aydin, 1988; Scholz et al., 1993). This dimensionality allows for a first-order favorability analysis of these structural settings. For example in a simple case of 10-km-long fault, the breakdown region associated with a fault termination is 0.2 to 2 km wide. The highest fault and fracture density and the most favorable permeability within this zone is directly at the tip of the primary fault (this zone of multiple, closely-spaced fault splays is called a horse-tail) and on the hanging wall side, where fluids rising along the dipping fault zone are likely to be focused (Figure 1A and 2A).

In a step-over with a primary fault length of 10 km, each primary fault tip is associated with a 0.2-2 km wide breakdown region. In order for the two breakdown regions to overlap, thus generating a contiguous zone of stress concentration and accentuated faulting and fracturing, the primarily faults can tip-out or overlap no farther apart than 0.2 to 2 km. Similarly, the total width of the combined breakdown region can be no wider than ~4 km. Step-overs, therefore that are wider than ~20% of the length of the primary faults are predicted to be relatively less favorable for accentuated fracture permeability. Fault density is likely to be highest near the fault tips, but on the inside (the step-side) of the faults, where the secondary faults that accommodate displacement transfer are located (Faulds and Varga, 1998). The most favorable geothermal are, where rising geothermal fluids are likely to be focused, is in the hanging wall on the inside of the step-over. (Figure 1B and 2B). As evidenced by several geothermal systems hosted by step-overs, fault and fracture density in the center of the step-over is favorable for geothermal-scale permeability as well (Faulds et al., 2010a, 2010b; Siler and Faulds, 2013). As examples of these scaling relationships, both Desert Peak and Brady's geothermal systems in the northwestern Great Basin are controlled by fault step-overs in the ~8-km-long km brady's fault zone and ~10-km-long rhyolite ridge fault zone respectively (Faulds et al., 2010a, 2012). Geothermal production in these systems, and presumably the most favorable fracture permeability, is confined to areas with relatively limited spatial extent well (<1-2 km wide) within the step-overs of each fault system (Figure 3).

An idealized accommodation zone between 10 km long faults can be no wider in the along-strike direction than ~4 km, in order to generate a contiguous breakdown region, and the primary fault can tips no farther apart than ~0.2 to 2 km. The across-strike width depends on the number of involved faults. Accommodation zones with primary faults spaced farther apart than ~20% of the fault length are therefore predicted to be relatively less favorable for high fracture permeability. Again, fault density and fracture permeability is likely to be highest near the tips of primary faults and on their hanging wall sides (Figure 1C and 2C). In fault terminations, step-overs and accommodation zones the most favorable conduits for geothermal upflow plunge down the dip of the involved, primary faults (Figure 2), requiring accurate and precise knowledge of structural geometry, especially fault dip, in order to accurately define drilling targets in the subsurface (e.g. Siler and Faulds, 2013).

Fault zone fracture permeability is also favored along fault strands that are critically stressed under ambient stress conditions. These critically stressed areas have a relatively higher likelihood of serving as fluid flow conduits (Sibson, 1994, 1996; Barton et al.,

1995; Morris et al., 1996). The tendency of a fault to be critically stressed for dilation, and therefore favorable for fluid flow, is dependent on the components of the stress field that are oriented orthogonal to the fault plane (Ferrill et al., 1999). To a first order and in a normal faulting stress regime, the angle between the minimum horizontal compressive stress, S_{Hmin}, and the fault strike is representative of the tendency of a fault to be critically stressed for dilation. Faults that strike at high angles to S_{Hmin} have the highest tendency to dilate, while faults that strike sub-parallel to S_{Hmin} have the lowest tendency to dilate. Predictably, throughout the extensional Great Basin, the majority of faults are oriented orthogonal to S_{Hmin} (Figure 4 inset; stress field calculated based on Hickman et al., 1998, 2000; Robertson-Tait et al., 2004; Davatzes and Hickman, 2006; Heidbach et al., 2008; Moeck et al., 2010; Blake and Davatzes, 2011, 2012; fault strikes from United States Geologic Survey, 2006) and therefore are well oriented for dilation. However, there is significant variation in fault strike throughout the Great Basin and the direction of S_{Hmin} is variable as well. As a result, certain areas contain an abundance of faults that are orthogonal to modern measured direction of S_{Hmin}, where as in other areas, ideally oriented known faults are less dense (Figure 4). Within areas where faults are generally oriented at a high angle to S_{Hmin} step-overs, accommodation zones, fault terminations with appropriately spaced primary faults (and especially areas characterized by more than one of these structural settings) are highly prospective for permeability and geothermal circulation.

4. PERMEABILITY FAVORABILITY: ICELAND

High-temperature geothermal systems in Iceland occur exclusively within the 40-50-km-wide plate boundary zone (Figure 5; Arnórsson, 1995). In this area new crust is generated within discrete volcanic rift segments (Sæmundsson, 1978, 1979; Gudmundsson, 1995). Volcanic rift segments are on the order of ~10s to 100 km long and are arranged in an en echelon, overlapping pattern within the plate boundary region (Sæmundsson, 1978, 1979; Gudmundsson, 1995, 2000b). Volcanic centers within these rift segments are associated with magma and heat supply from depth and robust magmatic construction by intrusion of shallow level magmatic material and with eruption of lava flows (Siler and Karson, 2009, 2012). Extending along-strike from the volcanic centers are axial fissure swarms where crustal construction is accommodated by lateral dike injection, effusive basaltic eruptions and normal faulting sub-parallel to the main rift trend (Walker, 1958; Sæmundsson, 1978, 1979; Gudmundsson, 1995, 2000b).

Both high-temperature (>200° C at 1 km depth) and low-temperature (<150°C at 1 km depth) geothermal systems in Iceland are characterized by elevated fracture permeability in rocks that otherwise have very low permeability (Ágústsson and Flóvenz, 2005; Richter et al., 2010). The two structural domains present in Iceland, volcanic centers and axial fissure swarms, both generate elevated fracture permeability. Though high-temperature geothermal systems most commonly occur local to volcanic center structural domains, fissure swarm structural domains host high-temperature geothermal systems as well (Figure 5; Arnórsson, 1995). The markedly different structural geometries of these two domains however, indicates that the character of permeability and possibly the overall permeability potential of each domain may be markedly different as well.

Volcanic rift segments are typically on the order of several 10s of km to 100 km long and 5-10 km in width (Sæmundsson, 1978, 1979; Gudmundsson, 1995, 2000b). Axial fissure swarms are characterized at the surface by axial fissures and faults (Figure 1D), which are probably the surface expression of axial dikes intruded in the subsurface. Volcanic centers are commonly characterized by radially oriented structures, including cones sheet swarms and calderas (Gudmundsson, 1995, 2000b; Siler and Karson, 2009, 2012). Even when a caldera or other radial structure is not evident at the surface, the common occurrence of sill-shaped shallow magma chambers beneath volcanic centers (Brandsdóttir et al., 1997), predict radially oriented structures (Gudmundsson, 2006, 2007). Using these idealized structural geometries and 10 km long primary faults in the fissure swarm, the breakdown region of concentrated stress at the tips of the axial faults is ~2 km (Figure 1D and 2D). The area where these primary faults intersect and interact with the radially oriented structures at the volcanic center (idealized at ~5 km in diameter, as is typical of calderas and cone sheet swarms; e.g. Siler and Karson, 2012) has the density of fault intersections and therefore highest likelihood for accentuated fracture permeability. We hypothesize that within volcanic rift systems, the areas within and along the inner margin of volcanic centers are the most favorable zones for fracture permeability. In these areas the interface between fissure swarm and volcanic center structural domains results in the highest density of structural intersections (Figure 1D and 2D). Locations where structures are at a high angle to S_{Hmin}, and therefore likely to be dilational, are the most favorable locations for accentuated fracture permeability and geothermal fluid flow.

The heat for fissure swarm hosted high-temperature magmatic geothermal systems in Iceland is provided by young magmatic/intrusive material that is injected laterally from the volcanic center (Sæmundsson, 1978; Einarsson and Brandsdóttir, 1980). Near volcanic centers the heat source is typically young magmatic/intrusive material intruded into the shallow crust beneath the volcanic center itself (e.g. Brandsdóttir et al., 1997). Interestingly, Arnórsson (1995) suggests that an overabundance of young intrusive material at the volcanic center may actually reduce permeability through closing of fractures. This point lends further support to the inner margin of volcanic centers as the most favorable permeability domain. We suggest that this area is associated with abundant fracture permeability provided by fault intersections and near enough to the requisite heat provided by young intrusions at the volcanic center, yet far enough from the densest area of intrusion, presumably in the heart of the volcanic center, for fracture permeability to remain open. There is, however, a temporal component that needs to be considered as well. Volcanic systems with evidence for relatively recent intrusion beneath the volcanic center are more likely to have fracture permeability hindered through closing of fractures while this affect is less likely at volcanic centers with relatively less recent intrusive activity.

As examples, both the Krafla and Hengill volcanic systems host known geothermal systems (Figure 6). At Krafla the volcanic center, as defined by the presence of the mapped caldera (Sæmundsson, 1978), the interpreted location of magma bodies beneath the caldera (Einarsson, 1978), and the mapped extent of the low-electrical resistivity cap at 800 m depth beneath the caldera (Halldórsdóttir et al., 2010), hosts a geothermal system (Figure 6A). The dense swarm of axial faults cutting through the Krafla caldera generate fracture permeability in both the Krafla geothermal system within the volcanic center and the Namafjall geothermal system on the outside of the volcanic center (Figure 6A). We suggest that the location of the Krafla geothermal field is controlled by fracture permeability associated with interaction of the dense axial fault swarm and radial structures within the caldera. Fracture permeability at Namafjall appears to be primarily related to the axial fault swarm. Krafla is characterized by

abundant, Holocene and historic eruptive and intrusive activity, so diminishing of permeability though closing of fractures by intrusion is possible (Arnórsson, 1995).

At Hengill, as no caldera is mapped, the extent of the volcanic center is indicated by the extent of the low-resistivity cap (among other features), which is centered on Hengill mountain (Figure 6B; Árnason et al., 2010). Both the Nesjavellir and Hellisheiði geothermal fields are appear to be associated with the dense swarm of axial fissures and faults cutting through the volcanic center, while the Hveragerði field is local to a less dense swarms of faults and fissures along the margin of the Hengill volcanic center (Figure 56) or perhaps associated with recently active faults within the South Iceland Seismic Zone (e.g. Pedersen and Gudmundsson, 2003). Though the Hengill area has Holocene eruptive and intrusive activity, the area has been less active in the Holocene than Krafla has and therefore may have less reduction in fracture permeability due to young intrusions relative to Krafla (Arnórsson, 1995). Mean faults strike at both Krafla and Hengill are near orthogonal to S_{Hmin}, though faults at Krafla are generally closer to orthogonal (Figure 6 insets). In both systems individual fault and fissure segments orthogonal to S_{Hmin} are the most critically stressed for dilation and thus more likely to act as fluid flow conduits.

5. PERMEABILITY FAVORABILITY: EAST AFRICA

Magmatic continental rifting in the East African Rift system is similar in both structure and character to magmatic rifting in Iceland (Karson and Curtis, 1989; Ebinger and Casey, 2001; Keir et al., 2006, 2009; Wright et al., 2006; Ebinger et al., 2008; Siler, 2011). Volcanic rift segments throughout the East African Rift system have similar dimension to volcanic rift segments in Iceland (Hayward and Ebinger, 1996; Ebinger and Casey, 2001), and are also characterized by structural domains analogous to Iceland's volcanic center and axial fissure swarm structural domains (Siler, 2011). Upper crustal magma chambers beneath volcanic centers (Ebinger et al., 2008; Keir et al., 2009) predict radially oriented structures in the East Africa Rift, while distal to volcanic centers, axial faults and fractures accommodating tectonic and magmatic extension dominate (Wright et al., 2006; Keir et al., 2009). Known geothermal systems in the East Africa Rift system tend to occur local to central volcanic complexes although, like in Iceland, axial fault systems are important for channeling recharge and host geothermal outflow in several locations as well (Simiyu, 2008; Kanda, 2011; Mutonga, 2013). This analogous structure indicates that fracture permeability and geothermal favorability in the East Africa Rift system may also be most favorable at the interface between the volcanic center and axial rift zone domains (Figure 1D and 2D), as it is in Iceland.

6. CONCLUSIONS

Extensive structural analysis of geothermal systems in the Great Basin indicate that many geothermal systems are hosted by horse-tailing fault terminations, step-overs or relay ramps in normal fault systems and accommodation zones between fault systems with opposing dip. The most prolific fracture permeability in these complex structural zones is generated in locations where stresses are concentrated local to fault tips and fault intersections and along fault segments that are critically stressed for dilation. Geothermal systems in magmatic rifts are controlled by both axial fault systems and radial volcanic center structures. We suggest that the most favorable location for permeability in magmatic rift segments is at the interface between volcanic centers and axial rift zones where radial volcanic center structures interact and intersect with axial faults and fissures. Locations where these structural domains have been subsequently rifted away from the active plate spreading zone also represent favorable permeability for off-axis, low-temperature geothermal systems. Thorough analysis of structural permeability associated with geothermal systems in magmatic rift zones is generally lacking, but our simplified conceptual model maybe applicable to geothermal systems in the East African rift system and in other magmatic rifting environments with analogous structure. Though there is certainly significant variation in geometry between different occurrences of these common structural settings, conceptualized models based structural data, quantitative and qualitative studies of basic structural principles (e.g. Figures 1 and 2), indicate the locations of the most prospective areas for favorable fracture permeability at the scale of individual prospects. Such structural models can be continuously adapted with site specific data and, along with other data sets, be used to develop data-based conceptual models specific to a given geothermal prospect and ultimately site geothermal wells.

ACKNOWLEDGEMENTS

This work was supported by Lawrence Berkeley National Laboratory under U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Geothermal Technologies Program, under the U.S. Department of Energy Contract No. DE-AC02-05CH11231. We thank the anonymous reviewer for their thoughtful remarks.

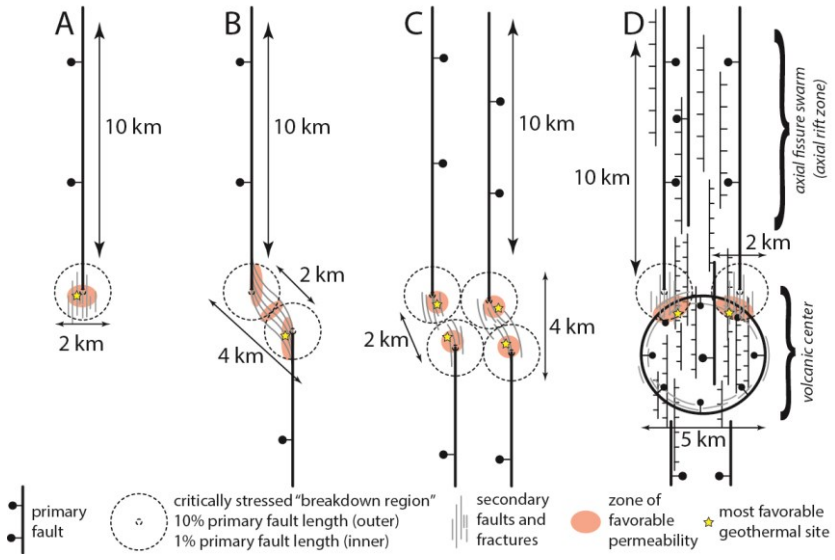

Figure 1: Map view conceptual models of common structural settings for geothermal systems A) horse-tailing fault termination, B) step-over or relay ramp in normal fault system, C) accommodation zone, and D) magmatic rift segment. A, B and C modified after Faulds et al. (2006, 2011).

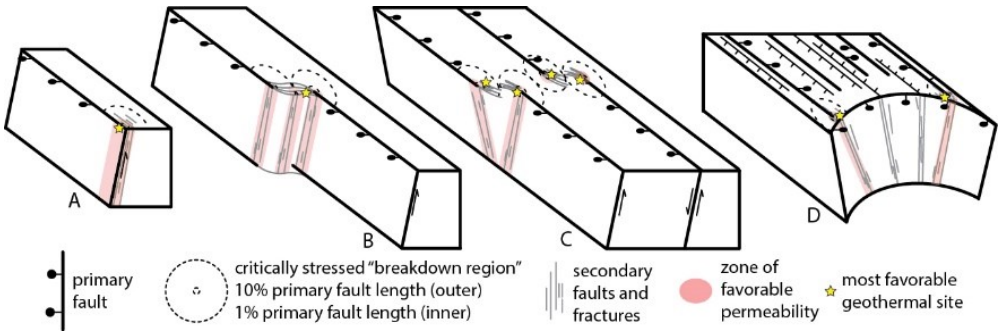

Figure 2: 3D conceptual models of the common structural settings for geothermal systems shown in Figure 1. A) horse-tailing fault termination, B) step-over or relay ramp in normal fault system, C) accommodation zone, and D) magmatic rift segment. A, B and C modified after Faulds et al. (2006, 2011).

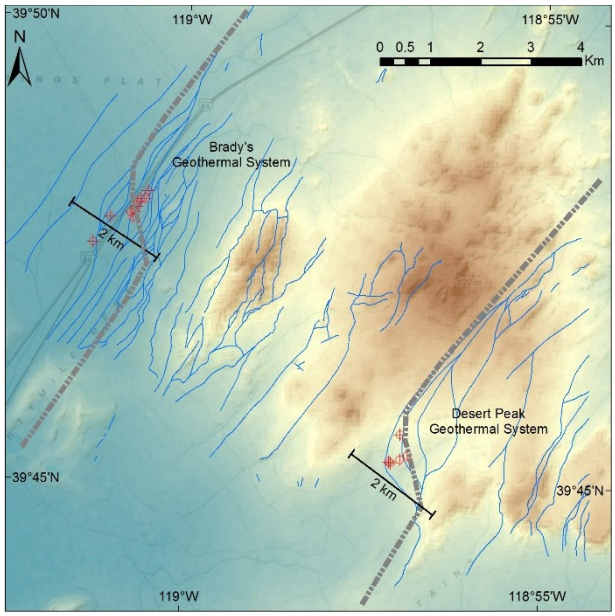

Figure 3: Map of the Brady's and Desert Peak geothermal systems in northwestern Nevada. Faults (blue) and geothermal well locations (red) from (Faulds et al., 2012). Both systems are hosted by left step overs in normal fault systems.

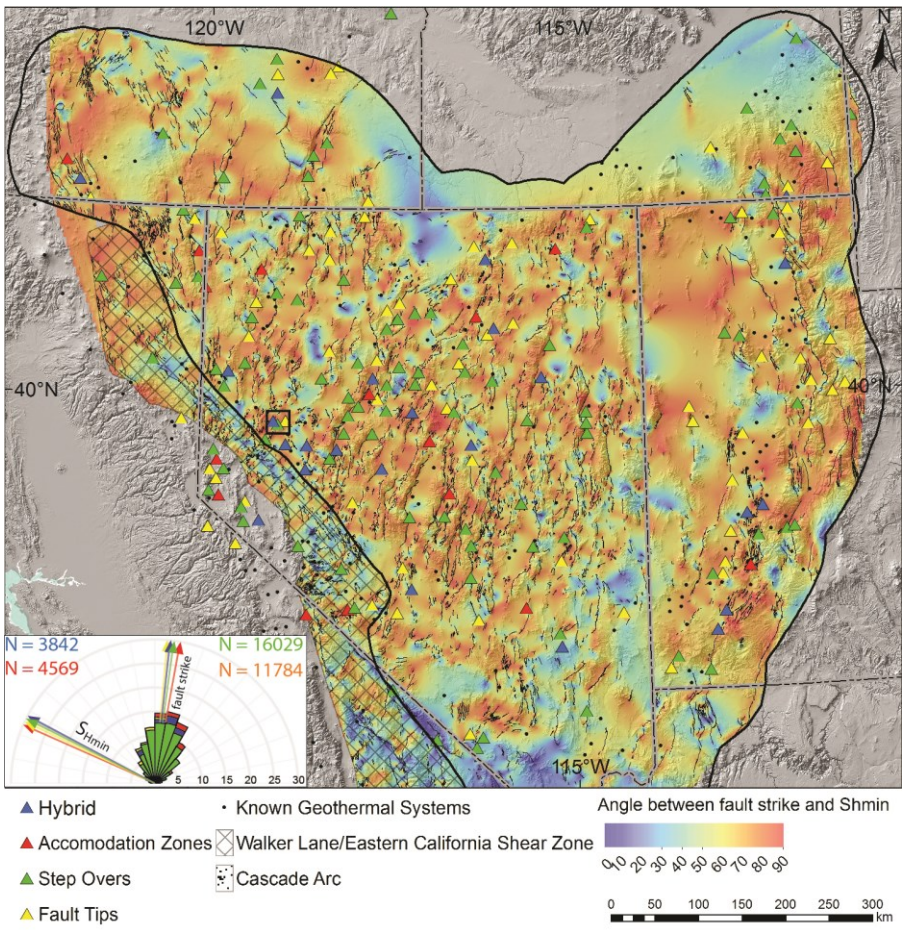

Figure 4: Map of the relative density of dilatant faults in the Great Basin, warm colors indicate a high angle between the S_{Hmin} direction and fault strike and cool colors indicate a low angle between the S_{Hmin} direction and fault strike. Inset shows the angular relationship between fault strike and the direction of S_{Hmin} for accommodation zones (red), step overs (green) fault tips (yellow) and hybrid systems (blue), which are characterized by more than one of the structural geometries. Black box shows the location of Figure 3.

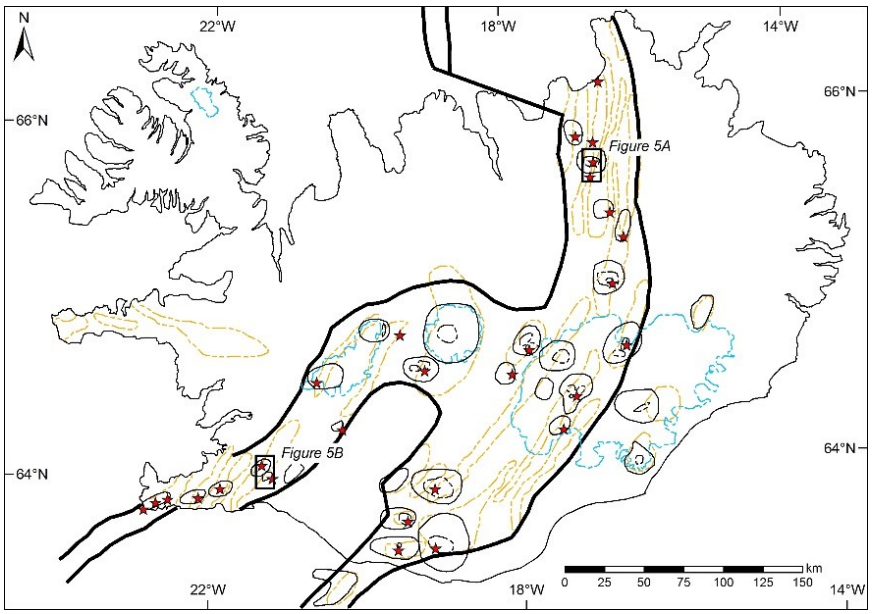

Figure 5: Tectonic map of Iceland. Boundaries of active plate boundary region (thick black lines), magmatic rift segments (dotted orange lines), volcanic centers (thin solid ovals) and, Holocene calderas (dotted black ovals) after (Sæmundsson and Jóhannesson, 1998). High-temperature geothermal systems (red stars) from (Arnórsson, 1995). Locations of Figures 6A and 6B shown with black boxes.

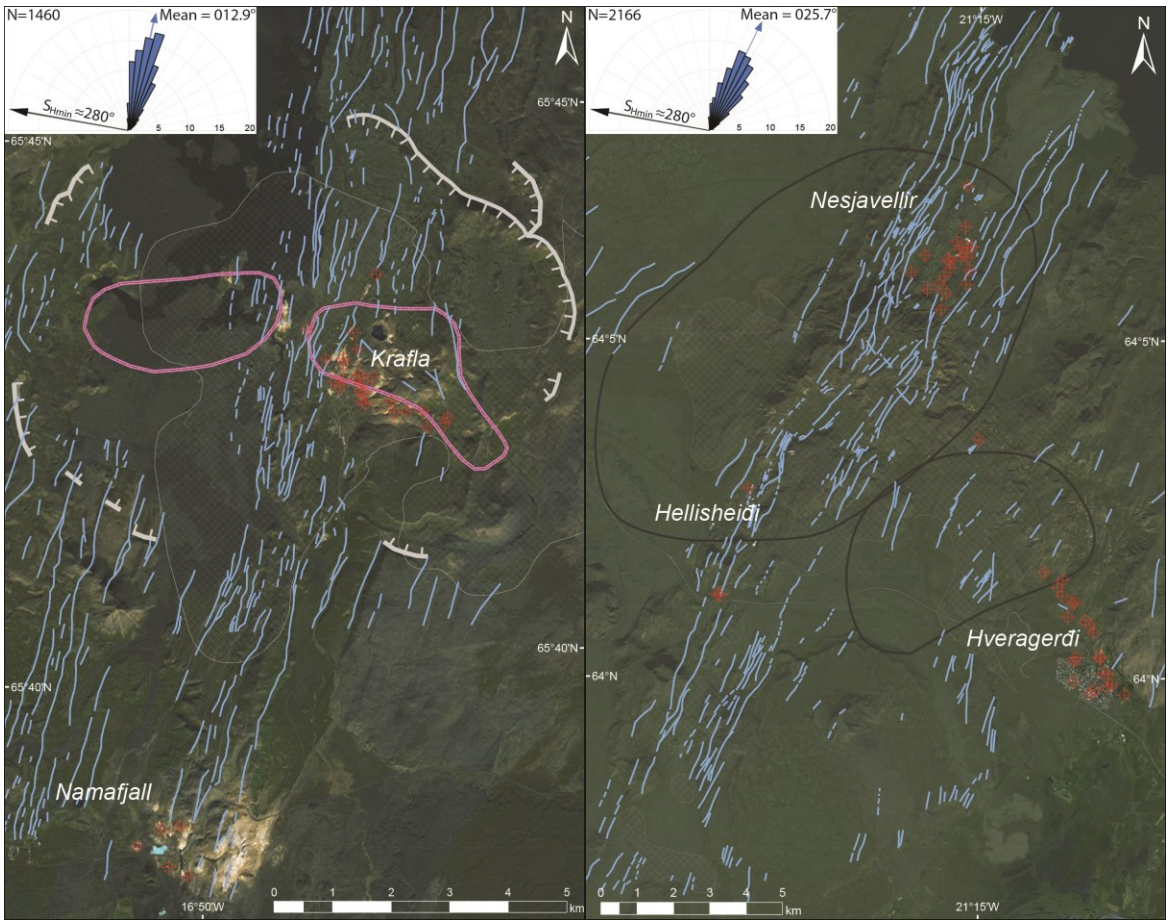

Figure 6: Geothermal systems within the Krafla (A) and Hengill (B) volcanic systems in Iceland. Fault and fissure traces are shown in blue, geothermal well locations in red (Krafla; Sæmundsson, 1978; Halldórsdóttir et al., 2010; Hengill; Árnason et al., 2010; Jousset et al., 2011). The extent of low electrical resistivity cap at ~800 m depth at Krafla (from Halldórsdóttir et al., 2010) and ~1000 m depth at Hengill (from Árnason et al., 2010) are shown with hatched pattern. The location of interpreted magma chambers (from Einarsson, 1978) are shown in pink and the location of caldera faults at Krafla (from Sæmundsson, 1978) are shown in white. The interpreted extent of volcanic centers local to Hengill (from Sæmundsson and Jóhannesson, 1998) **in black. Insets show fault strikes (5° bins) in blue for each system and the Nuvel 1A plate spreading direction (DeMets et al., 1990, 1994) as a proxy for S_{Hmin}.**

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